

# SOLAR ELECTRIC PROPULSION (SEP) FOR HUMAN SPACE EXPLORATION

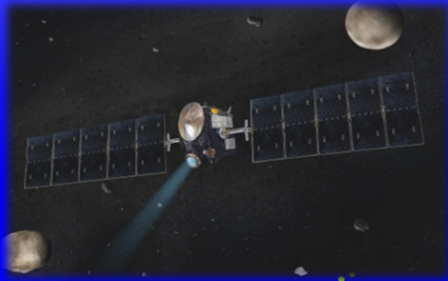
April 6, 2011

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*California Institute of Technology*

# SEP brings dramatic improvements to deep-space missions

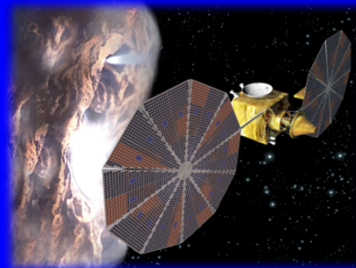
## Multiple rendezvous for small bodies

Enables many asteroid and comet missions that are impractical without SEP



## Reduced number of mission critical events

e.g., orbit insertion, earth avoidance, response to anomalies.....



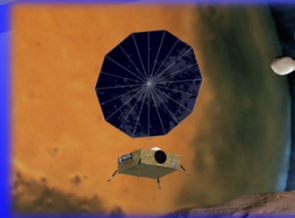
## More flexible launch opportunities

More frequent launch opportunities  
e.g., Dawn delay was possible to accommodate Phoenix launch



## Control of arrival conditions

Achieve lower speed arrival or control arrival time for Mars or Venus entry  
Change direction and velocity of approach to reach more landing sites



## More mass delivered to destination

Could enable more mass on smaller (and cheaper) launch vehicles  
Provides performance margin and resilience to mass growth

## Shorter trip times

Might expand feasible mission set beyond the asteroid belt including return of samples to Earth



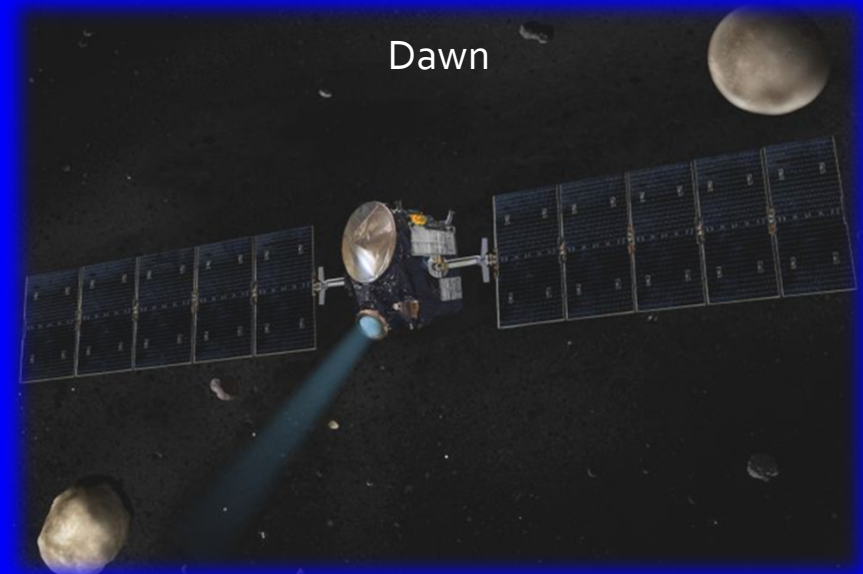
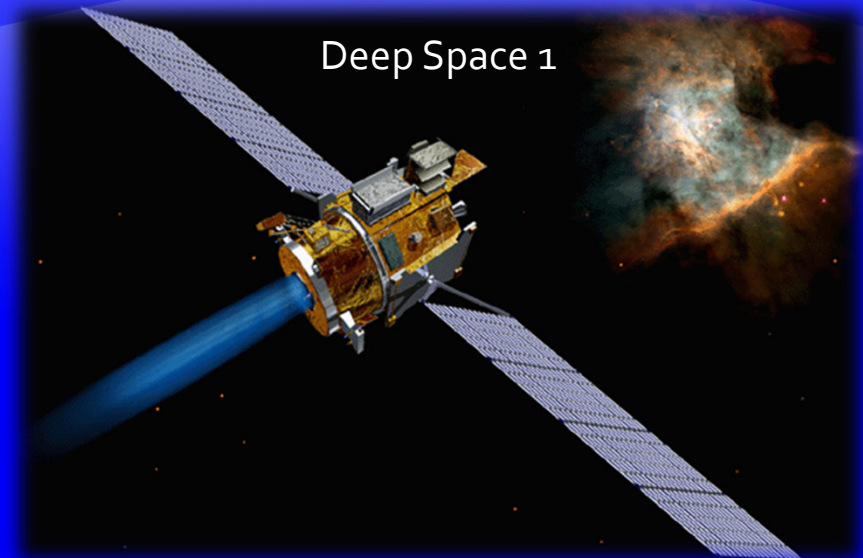
# SEP Has Been Used on Two NASA Deep Space Missions – So Far

## Deep Space 1:

- ♦ Technology Demonstration Mission
- ♦ Retired the following risks:
  - ♦ Thruster life
  - ♦ Guidance, navigation and control of an SEP spacecraft
  - ♦ Mission operations Costs
  - ♦ Spacecraft contamination
  - ♦ Communications impact
  - ♦ Electromagnetic compatibility

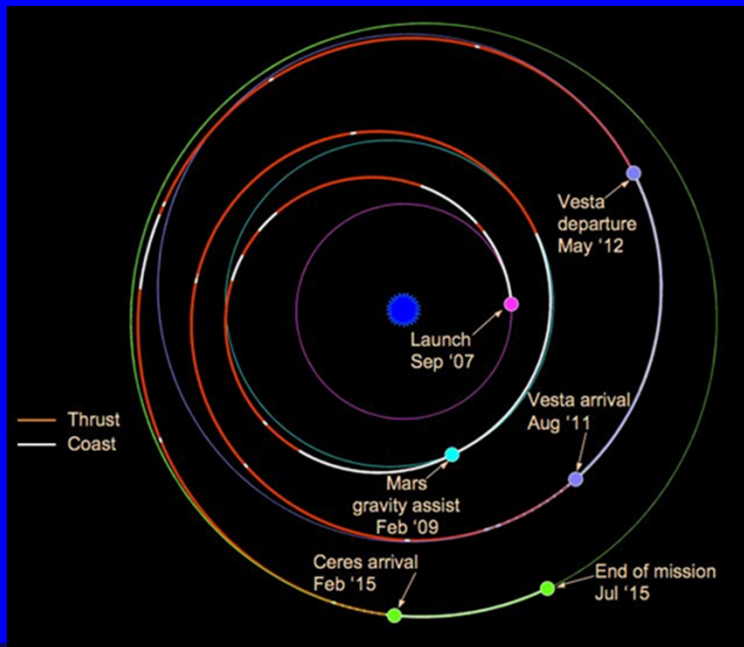
## Dawn:

- **The use of SEP on Dawn reduced the cost of a multiple main belt asteroid rendezvous mission from New Frontier-class to Discovery-class – a difference of over \$200M**



# Current Status: Dawn

- ♦ Will orbit **both** the main-belt asteroid Vesta and the dwarf planet Ceres
- ♦ Launched: September 2007
- ♦ 1218 kg launch mass (dry mass of 750 kg)
- ♦ 10-kW Solar Array (at 1 AU)
- ♦ **~21,200 hours of thrusting with the ion propulsion system and operating flawlessly**
  - ♦ Approximate  $\Delta V$  delivered to date: > 6 km/s
  - ♦ Xenon used to date: 230 kg (425 kg loaded)
- ♦ July 2011 arrival at Vesta





# Current Status: International

## SMART-1: Small Mission for Advanced Research in Technology

- Launched: September 2003

## Hayabusa: Near-earth asteroid sample return

- Launched: May 2003
- Returned: June 2010

## GOCE: Gravity field and steady-state Ocean Circulation Explorer

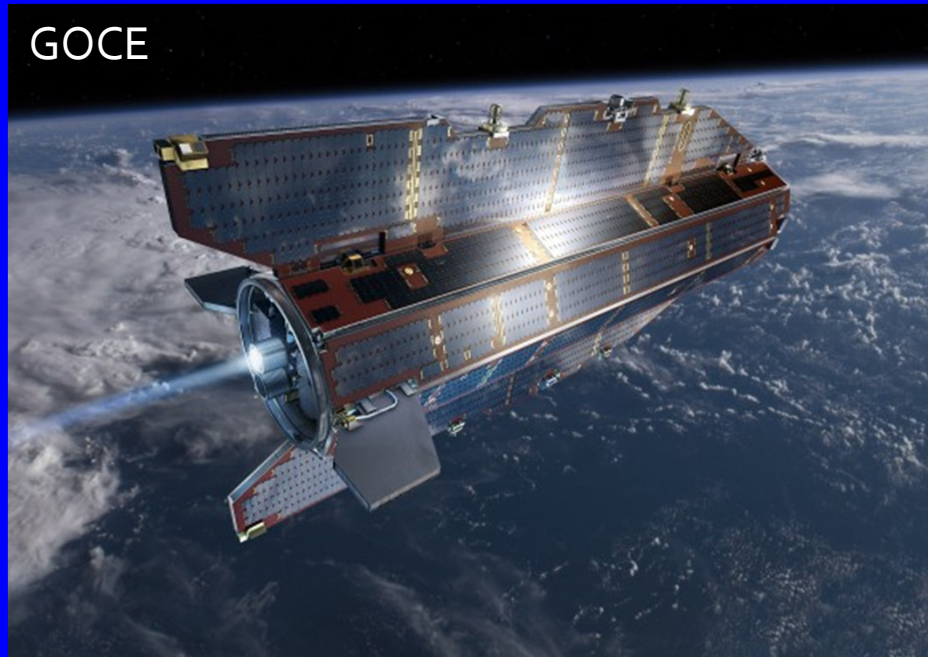
- Launched: March 2009



Hayabusa



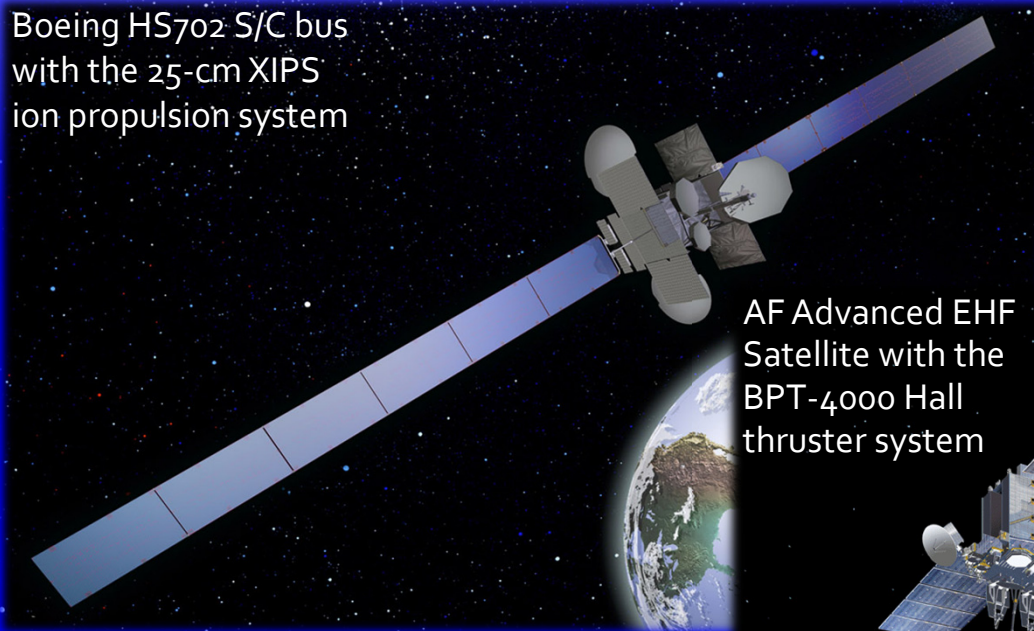
GOCE



# Current Status: Commercial

- ◆ **53 commercial satellites** now flying with xenon ion propulsion
- ◆ Commercial satellites now flying with up to **24 kW** of solar power at beginning of life

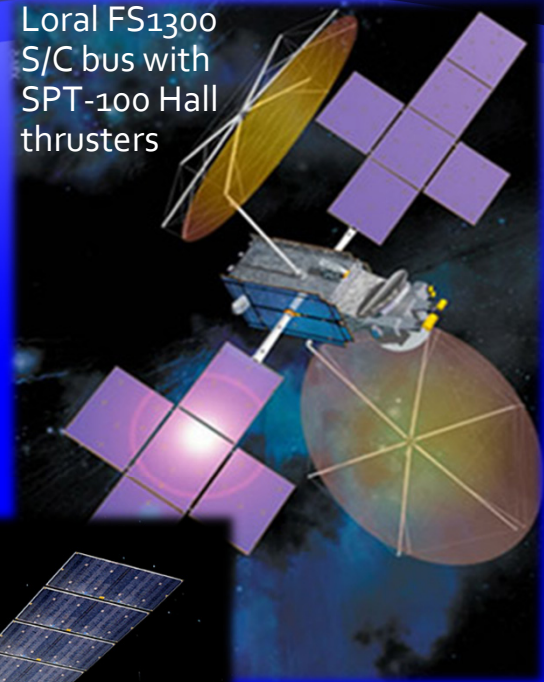
Boeing HS702 S/C bus with the 25-cm XIPS ion propulsion system



AF Advanced EHF Satellite with the BPT-4000 Hall thruster system



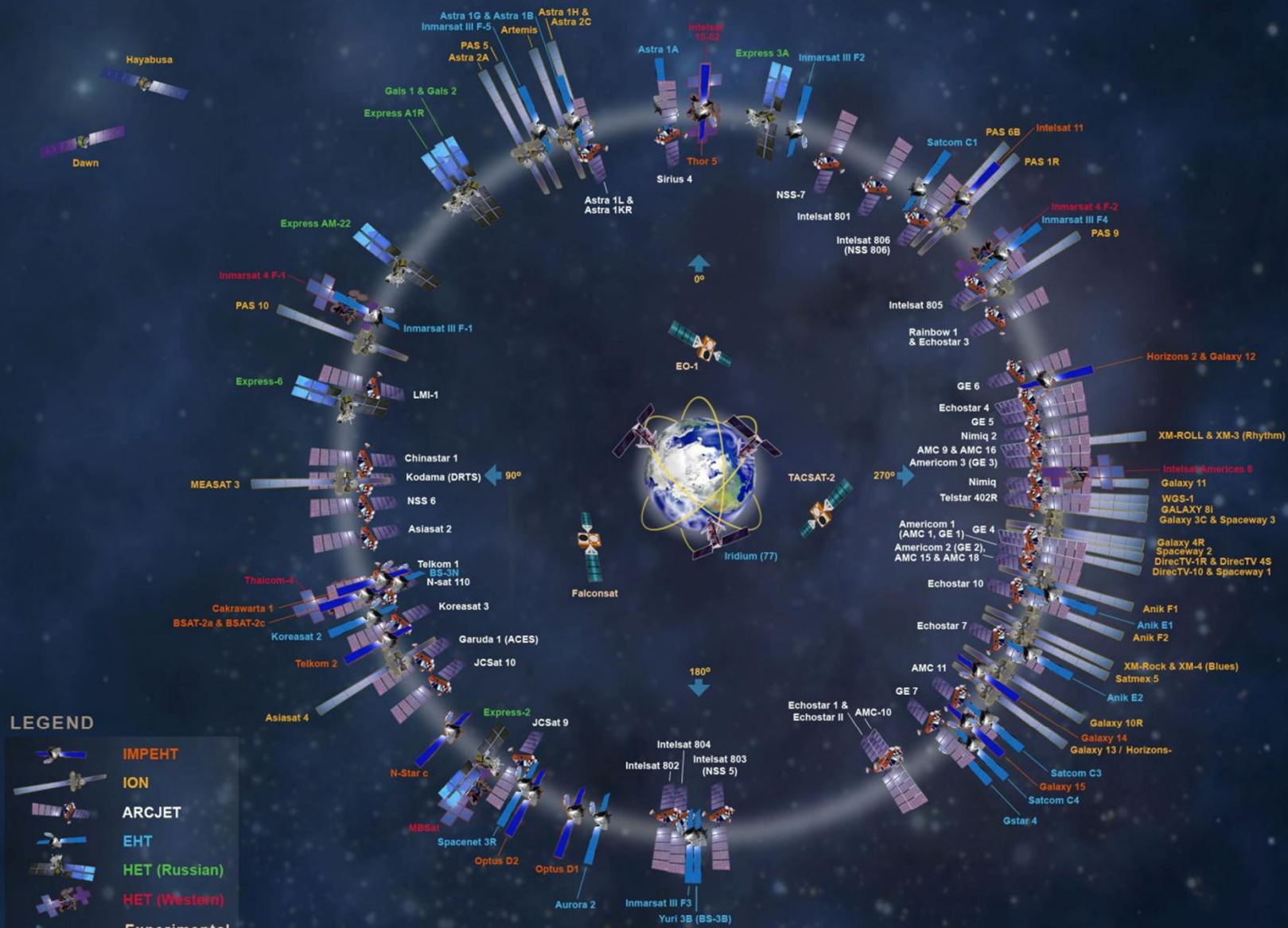
Loral FS1300 S/C bus with SPT-100 Hall thrusters



- High power (> 20 kW) is now routine on commercial satellites
- Electric propulsion now used by almost all major satellite providers because it provides a significant economic benefit to the end user



# Operational Satellites with Electric Propulsion



Cumulative Number of Satellites Employing EP = 226  
 Number of Satellites Employing Aerojet EP = 156

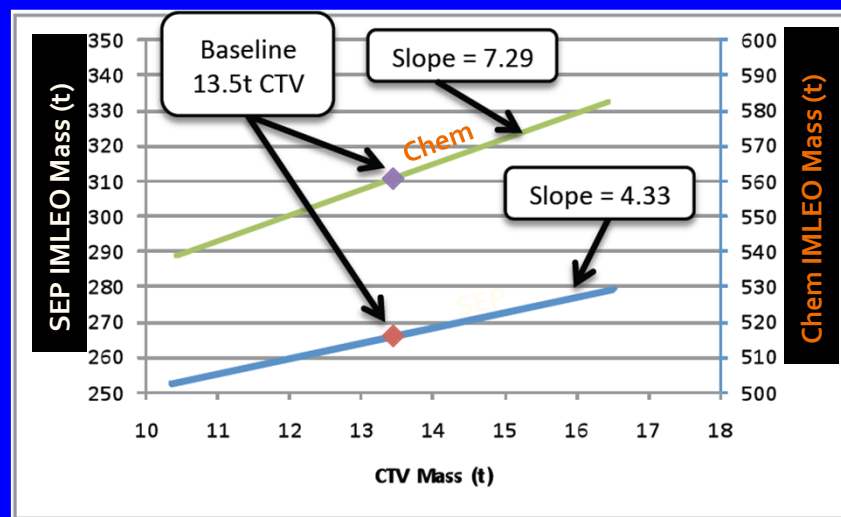
**AEROJET**

# Benefits of SEP for Human Space Exploration

- ◆ Reduces the number of HLLV's required by approximately a factor of two
- ◆ Provides a significantly better "gear" ratio than chemical stages
- ◆ Increases mission flexibility in terms of departure and return windows
- ◆ Affords more "graceful," less catastrophic propulsion system failure modes
- ◆ Provides substantial power at the destination and during coast periods
- ◆ Provides improved extensibility to missions beyond near-Earth asteroids

From the HEFT-I study

Area	SEP (100 t)	SEP (70 t)	Chem (100 t)	Chem (70 t)
# of Unique Elements	7	7	5	5
Total # of Elements	9	11	9	12
# Launches (HLLV)	3	5	6	9
# AR&Ds	8	9	9	12
# of Undocks	10	14	10	13
# Propellant Transfers	0	0	0	0
Chemical Prop Burns	7	9	14	19
Mission Lifetime	841 Days	930 Days	821 Days	1091 Days
Crew Time	394 Days	394 Days	371 Days	371 Days
IMLEO Mass (t)	254	262	537	591
NEO Arrival Stack Mass (t)	57	57	109	121

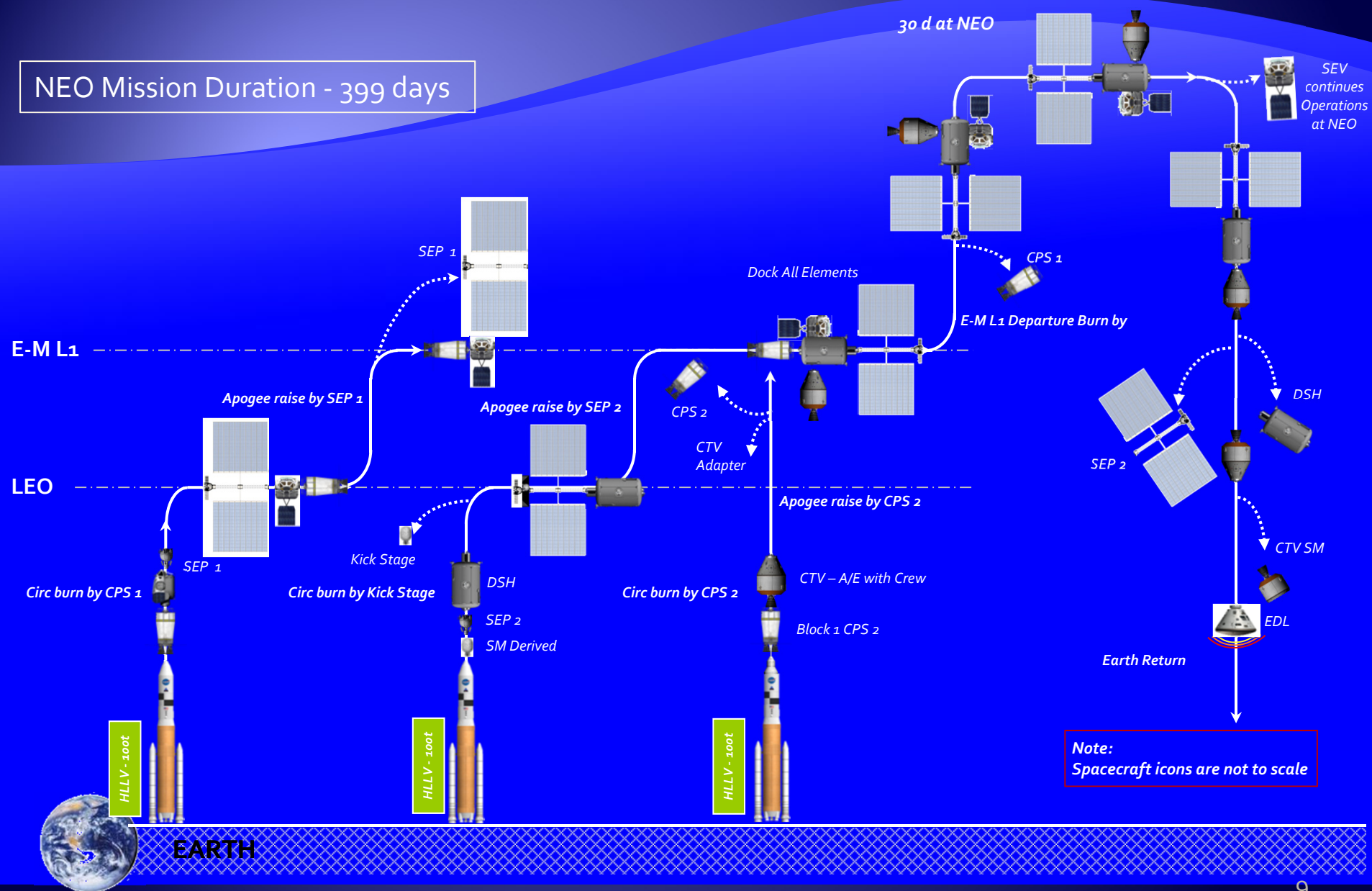


SEP provides better "gear" ratio than Chem

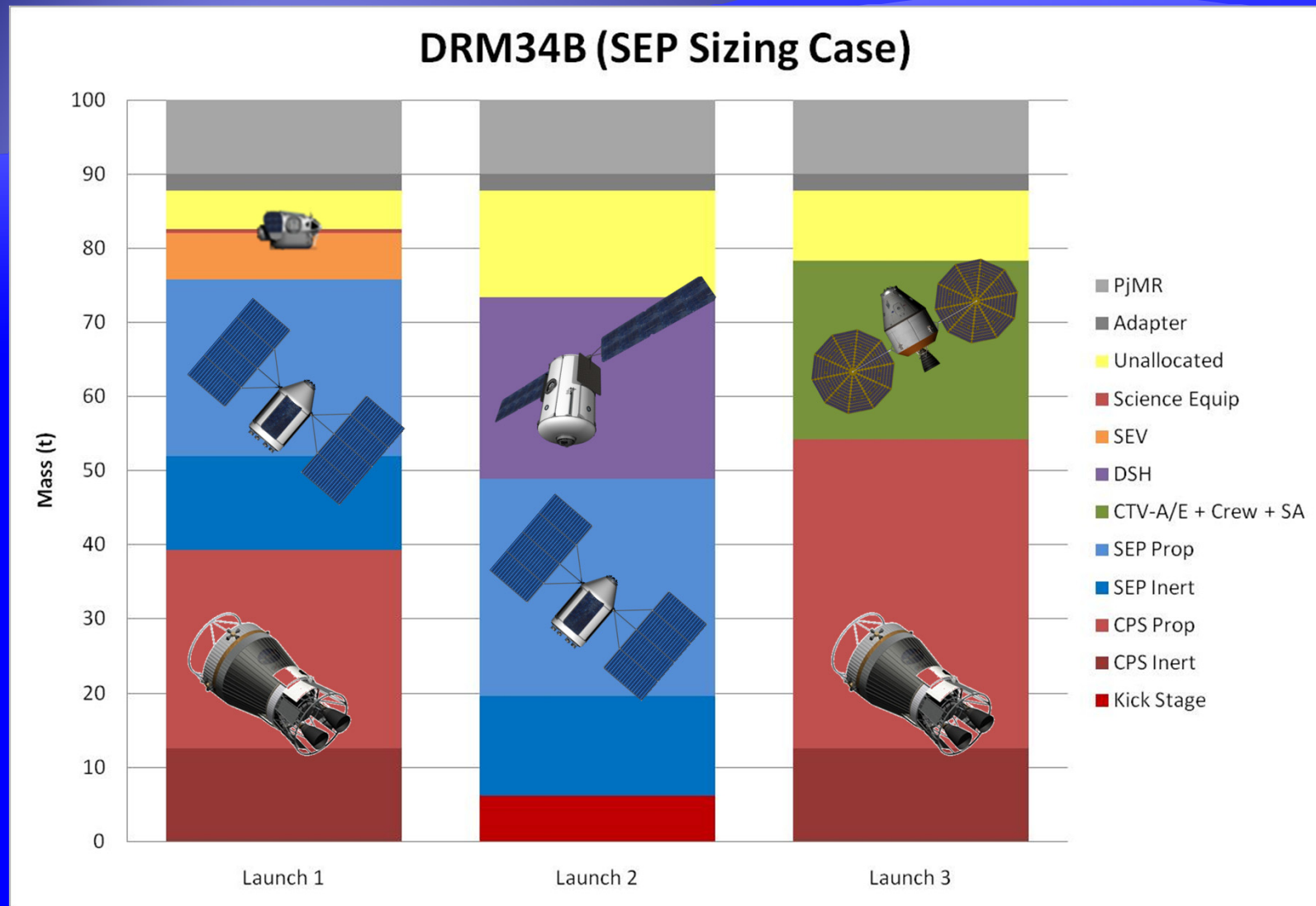


# EXAMPLE: DRM<sub>34</sub>B – Full Capability NEO Crewed Mission with 100 t HLLV

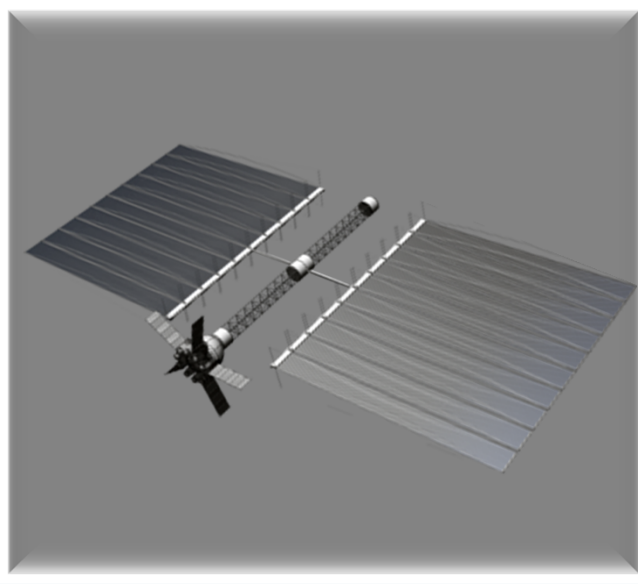
NEO Mission Duration - 399 days



# Launch Vehicle Stacks for DRM<sub>34</sub>B



# HEFT-I Solar Electric Propulsion Freighter



## Design Constraints/Parameters

Output of Solar Arrays (kW)	300
ISP (s)	2000
Alpha Sizing Values	
EPS Thrusters (kg/kW)	1.5
Power Processing Units (kg/kW)	4
FAST Arrays (kg/kW)	6.33
TCS (kg/kW)	1.8
Total Vehicle Alpha (kg/kW)	35.4
Batteries 2hrs eclipse at 80% DoD	
PMAD sized for 1kW peak	
Thrust through CG	
<1% array offpoint	
Total Efficiency	50%

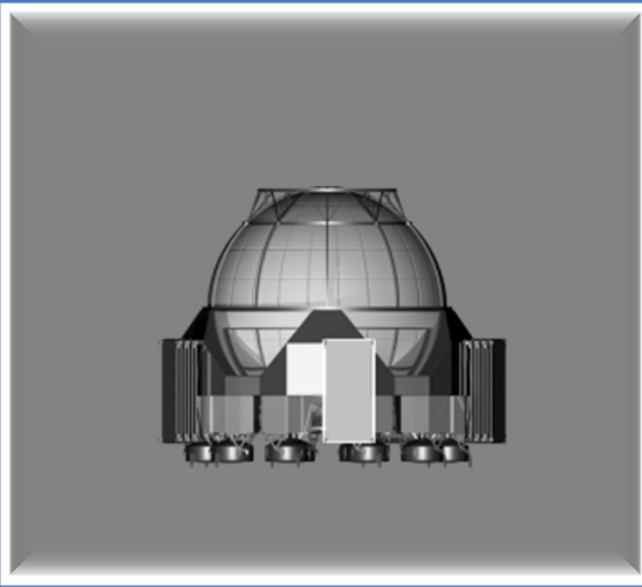
## Description

The Solar Electric Propulsion (SEP) freighter is used to transfer cargo between LEO, Earth-Moon L1 and Near Earth Objects (NEOs like 2008 EV5). For NEO missions this stage provides low thrust propulsion to the Deep Space Vehicle (DSV) after a Cryogenic Propulsion Stage (CPS) does the initial Trans-NEO Injection (TNI). The SEP freighter inserts the DSV into NEO vicinity and returns the DSV back from the NEO. The SEP is made up of a core truss or boom, two solar wings, and an Electric Propulsion Module (EPM). The solar wings are made up of 20 total (10 per wing) 15kW DARPA/Boeing FAST arrays. The EPM uses 30 kW Hall Effect Thrusters to deliver thrust at 2000 sec of specific impulse using xenon for propellant.

Category	Mass, kg
Structure (Boom)	1,218
Protection	0
Propulsion	3,147
Hall Effect Thrusters	428
Power Processing Units	1,140
Xenon Feed & Press System	620
RCS Thrusters	217
RCS GH2 System	319
RCS GO2 System	422
Power	2,399
FAST Arrays	1,899
Batteries	138
PMAD	363
Control	0
Avionics	396
Environment (TCS)	528
Other	0
Growth	2,306
DRY MASS SUBTOTAL	9,994
Non-cargo	617
Pressurization Helium	7
Unused Fuel	461
Unused Oxidizer	149
Cargo	0
INERT MASS SUBTOTAL	10,612
Non-propellant	0
Propellant	22,380
Xenon	21,799
RCS GH2	83
RCS GO2	498
TOTAL WET MASS	32,992

BBC is for SEP #2, propellant for SEP #1 is 22,361 kg

# HEFT-I Electric Propulsion Module



## Description

The Electric Propulsion Module (EPM) is one of the modules that make up the Solar Electric Propulsion (SEP) freighter. It structurally connects to the SEP core truss or the back of another EPM and has power and control input connections. Xenon propellant is stored in a spherical tank that is protected by MMOD shielding which makes up the core of the module. The EPM takes power as input at 300V and provides thrust at 2000 sec specific impulse through 10 30kW Hall Thrusters. These thrusters are located on 5 thruster modules that are identical and consist of the Hall thrusters, and associated thermal, power, and propellant management systems.

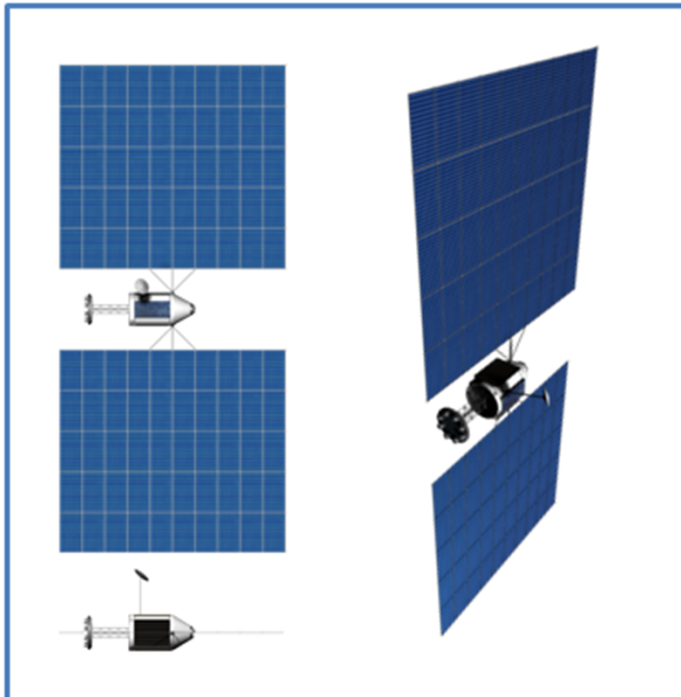
## Design Constraints/Parameters

Output of Solar Arrays (kW)	300
ISP (s)	2000
30 kW Hall Thrusters	10

Category	Mass, kg
Structure (Boom)	0
Protection	0
Propulsion	1,358
OMS Fuel Tanks	617
RCS Fuel Tanks	319
RCS Oxidizer Tanks	422
Power	1,568
Thruster Mass	428
PPU Mass	1,140
Control	0
Avionics	0
Environment (TCS)	0
Other	0
Growth	0
<b>DRY MASS SUBTOTAL</b>	<b>2,926</b>
Non-cargo	0
Cargo	0
<b>INERT MASS SUBTOTAL</b>	<b>2,926</b>
Non-propellant	0
Propellant	11,064
<b>TOTAL WET MASS</b>	<b>13,990</b>



# HEFT-II Solar Electric Propulsion Freighter



## Design Constraints/Parameters

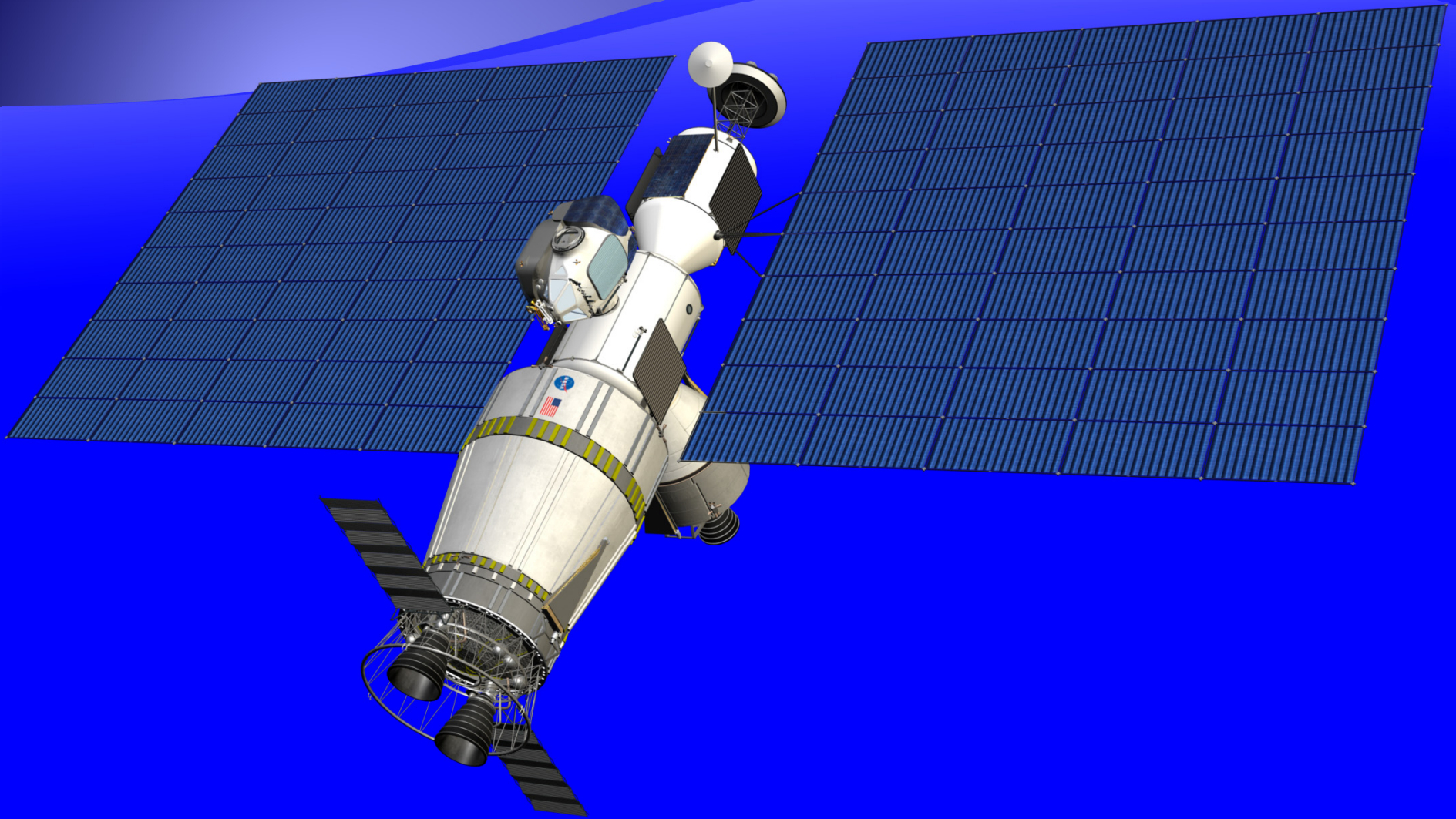
<b>Total Vehicle Alpha (kg/kW)</b>	<b>40.60</b>
<b>Large Solar Array</b>	
EOL Generation (kW)	320
Aspect Ratio	1:1
Structure	Square Rigger
Cell Type / Efficiency	IMM / 34%
Specific Power (W/kg)	121
<b>Electric Propulsion System</b>	
# Hall Effect Thrusters	8
ISP(s)	2000
Power (kW) (Nom. / Max)	37.5 / 50
# Xe Storage Tanks	8
Xe Tank diameter (m)	1
Xe Tank length (m)	3.68
Xe Ullage (%)	5
Xe residuals (%)	0
Thermal Rejection (kW)	15
Radiator Type	Loop Heat Pipe

## Description

The SEP-1 freighter is used to transfer cargo between LEO and Earth-Moon L1 (EM-L1). It carries 23,800 kg of xenon stored as a super critical fluid in six seamless aluminum-lined, graphite composite overwrapped tanks each 1-m dia. x 4-m long. The SEP-2 freighter is used to transfer cargo from LEO to EM-L1 and to transfer the crew to and from the near-Earth asteroid. It carries 29,794 kg of xenon in eight tanks identical to those used on the SEP-1 vehicle. Both SEP freighters are built around 320-kW end-of-life, planer SquareRigger deployable solar array structures that use triple junction, inverted metamorphic photovoltaic cells with 34% conversion efficiency. The electric propulsion system on each vehicle is two-fault tolerant and consists of eight 50-kW Hall thrusters with a specific impulse of 2000 s and conventional power processing units with an efficiency of 95%.

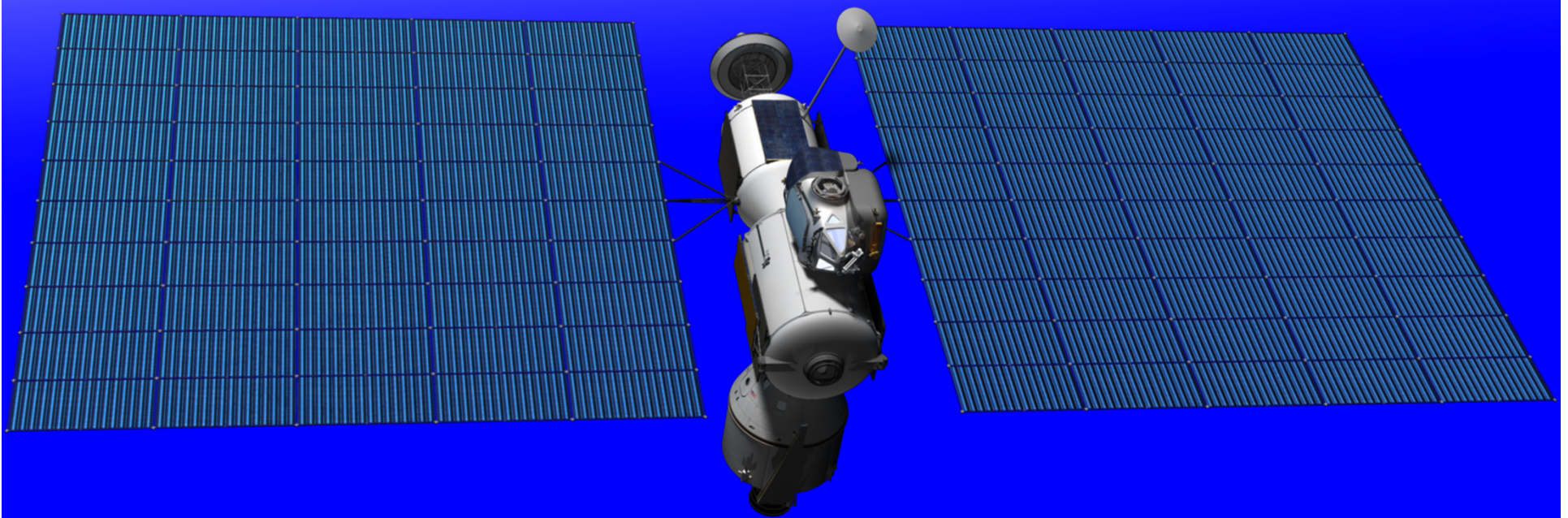
Category	SEP -1	SEP -2
<b>Structure</b>	<b>1,731</b>	<b>1,731</b>
<b>Protection</b>	<b>0</b>	<b>0</b>
<b>Propulsion</b>	<b>2,736</b>	<b>3,043</b>
Ion Propulsion System		
Hall Thrusters	605	605
Thruster Gimbals	303	303
PPUs	840	840
Xenon Feed System	52	52
Xenon Storage	919	1,225
<b>Control</b>	<b>450</b>	<b>450</b>
RCS	210	210
ACS (CMGs)	240	240
<b>Power</b>	<b>3,028</b>	<b>3,028</b>
Large Solar Array	2,651	2,651
Body Mounted Array	58	58
PMAD	268	268
Batteries	51	51
<b>Avionics</b>	<b>124</b>	<b>124</b>
<b>Thermal</b>	<b>434</b>	<b>434</b>
<b>Growth (30%)</b>	<b>2,551</b>	<b>2,643</b>
<b>DRY MASS SUBTOTAL</b>	<b>11,055</b>	<b>11,453</b>
<b>Non-cargo</b>	<b>1,216</b>	<b>1,538</b>
Residual OMS Propellant	1,193	1,490
Residual RCS Propellant	23	48
<b>INERT MASS SUBTOTAL</b>	<b>12,271</b>	<b>12,991</b>
<b>Non-propellant</b>	<b>0</b>	<b>0</b>
<b>Propellant</b>	<b>23,973</b>	<b>30,033</b>
Xenon	23,860	29,793
RCS Fuel	113	240
<b>TOTAL WET MASS</b>	<b>36,243</b>	<b>43,024</b>

# HEFT-II SEP Freighter

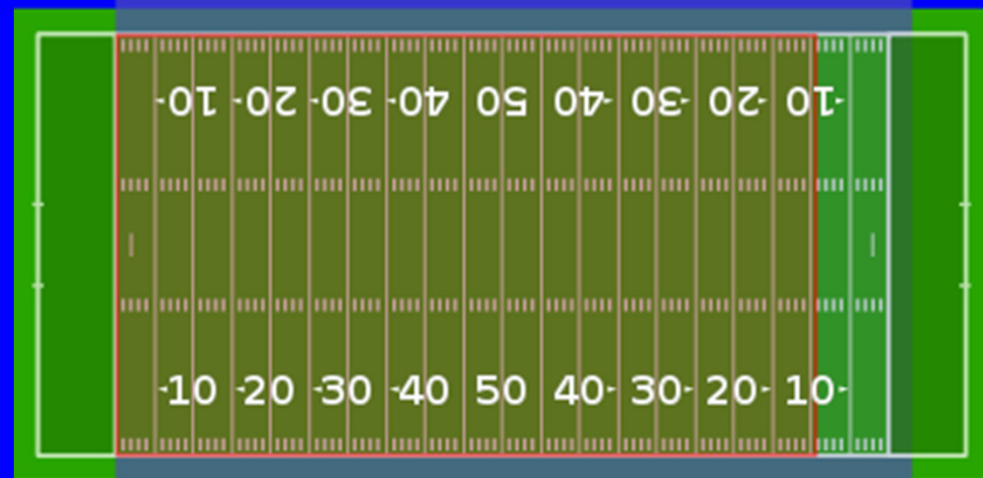
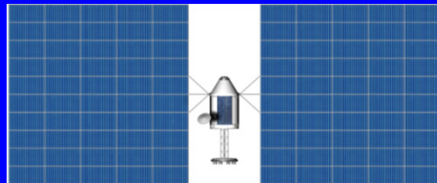
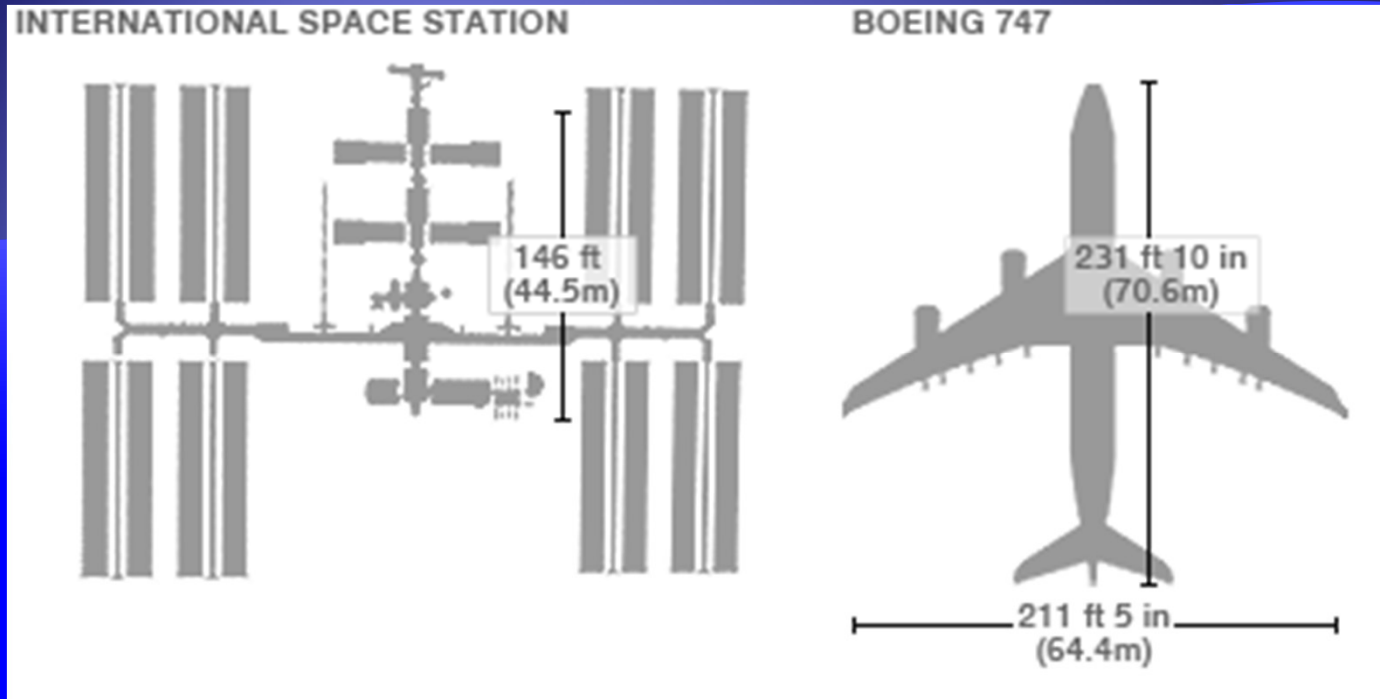




# HEFT-II SEP Freighter



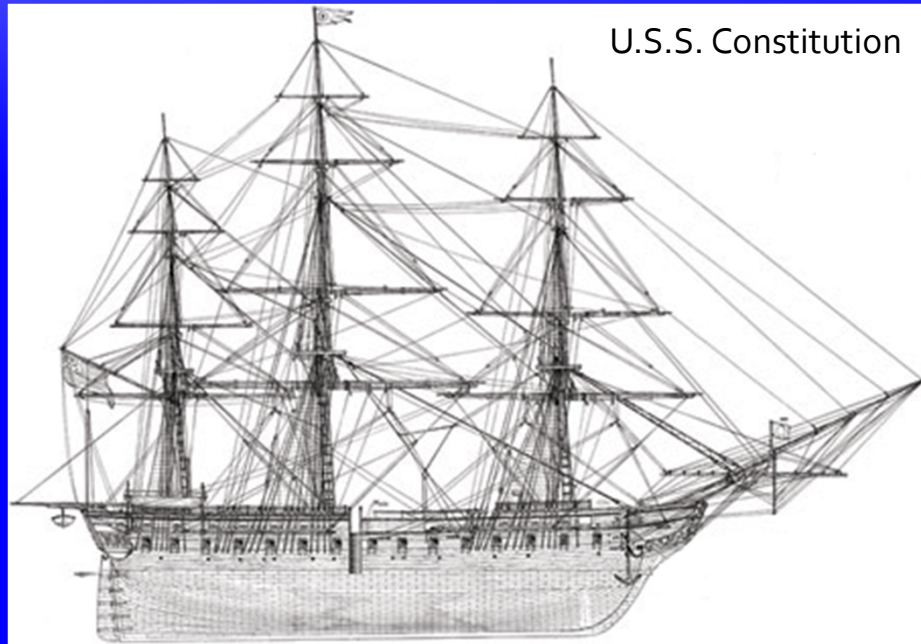
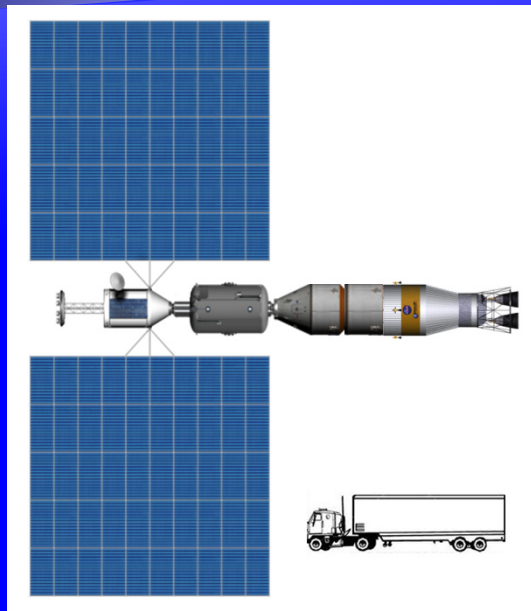
# SEP Size Comparison 1



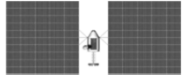
The area of one acre (red) overlaid on a football field (green) and soccer field (blue).



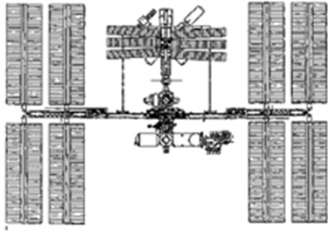
# SEP Size Comparison 2



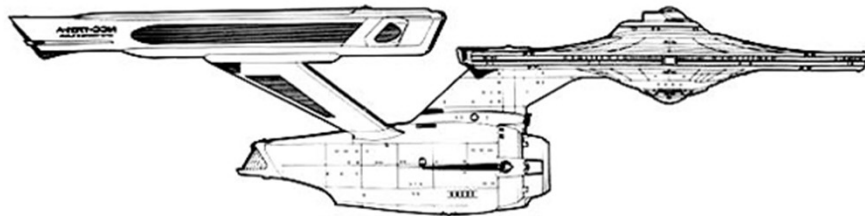
# SEP Size Comparison 3



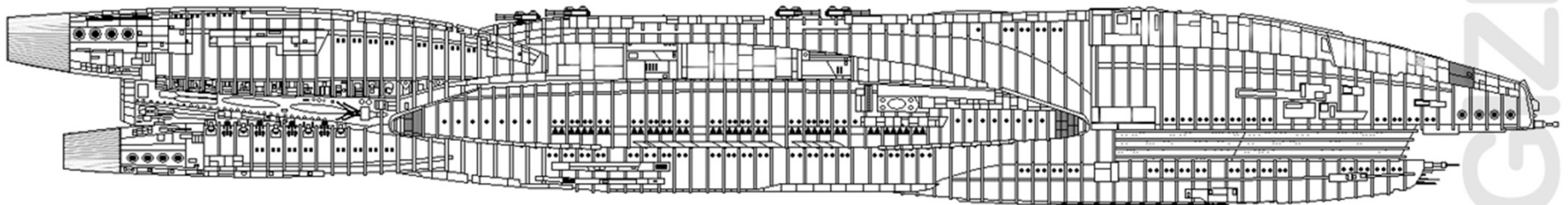
SEP Freighter: 50 meters



International Space Station: 107.4 meters

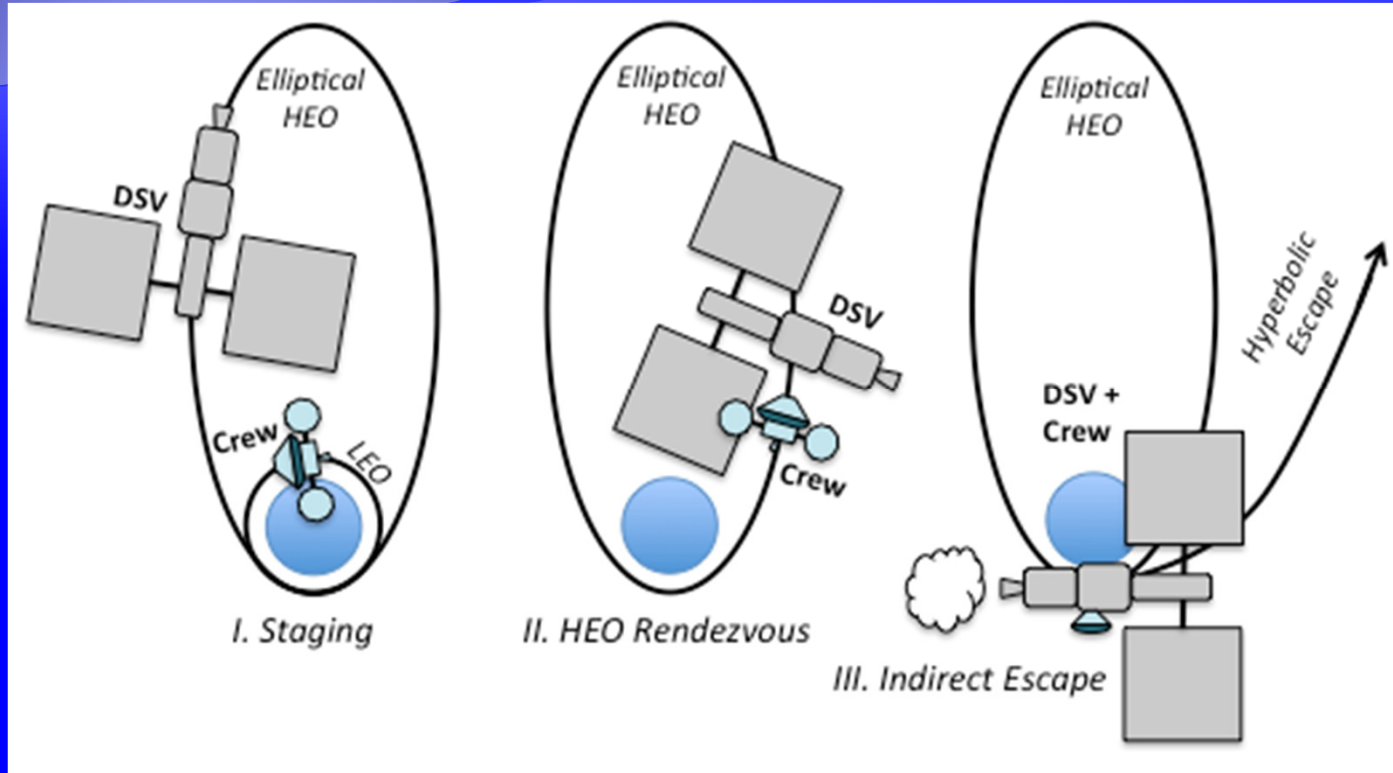


USS Enterprise (NCC-1701-A): 288.6 meters



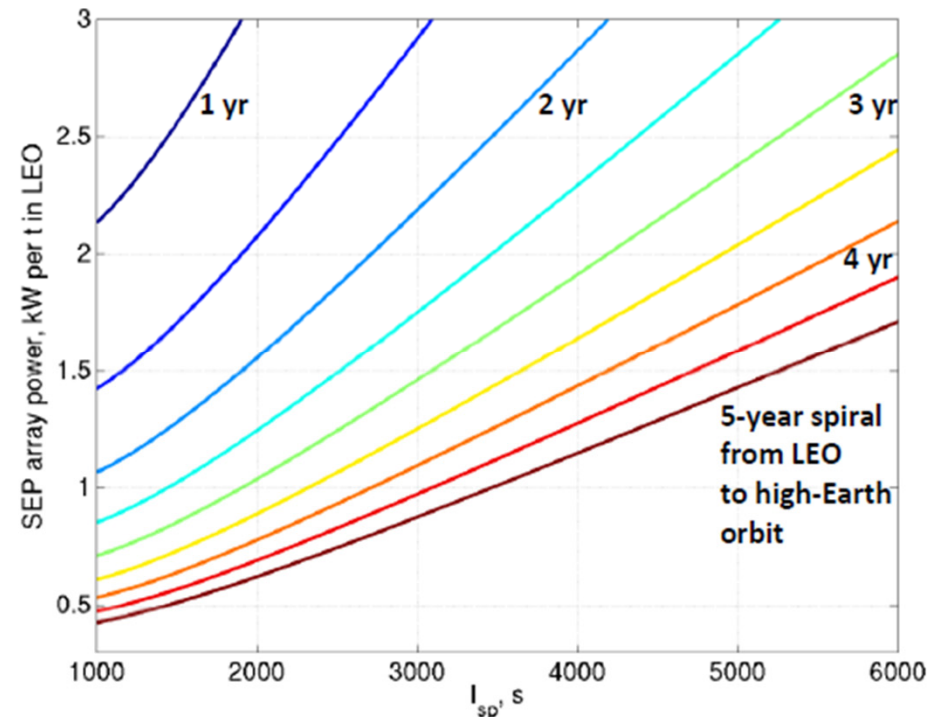
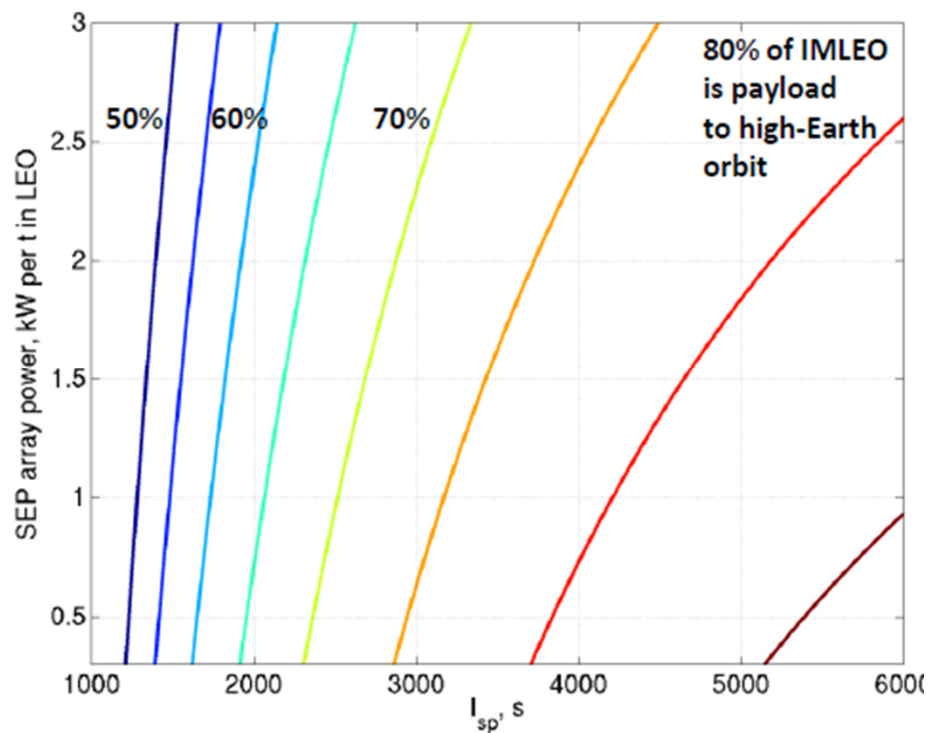
Battlestar Galactica (New Series): 615 meters

# Solar Electric Propulsion for Flexible Human Space Exploration



*Damon Landau and Nathan Strange,  
Jet Propulsion Laboratory, California Institute of Technology  
Jonathan Battat, Massachusetts Institute of Technology*

# SEP Spiral

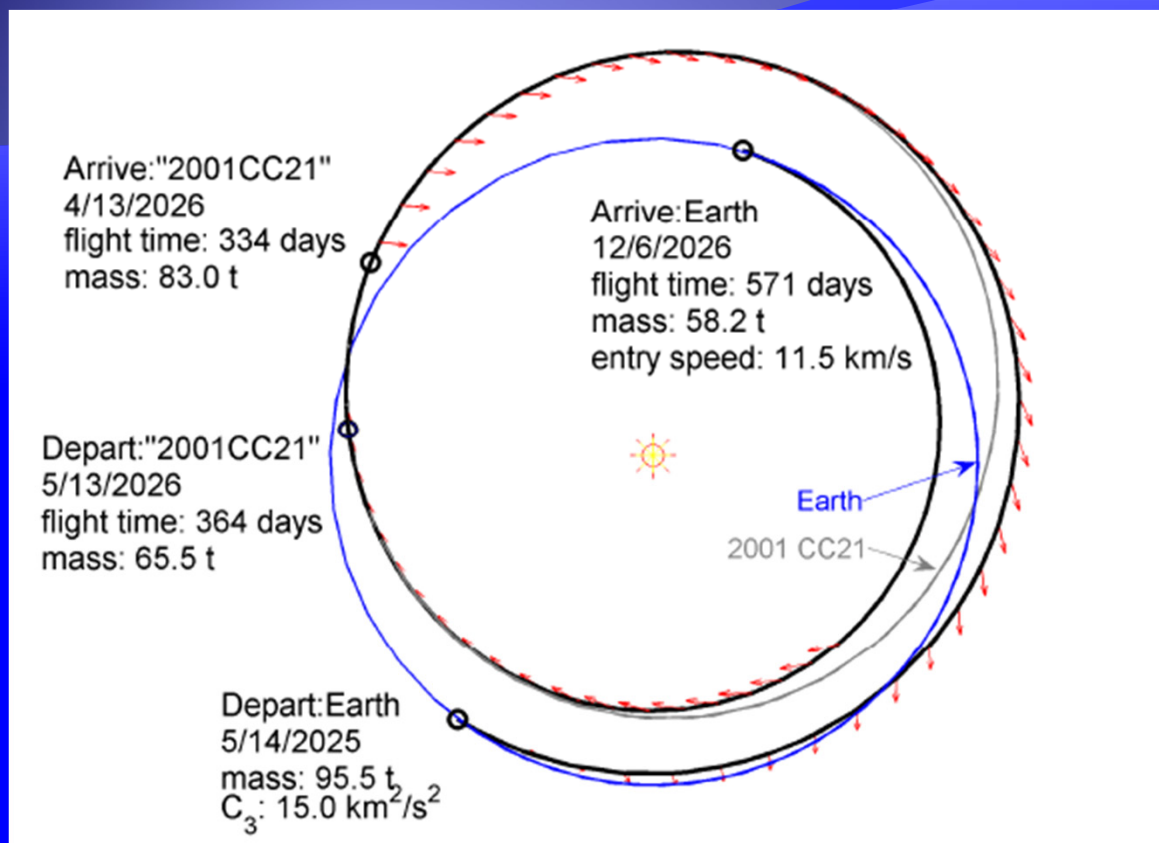


SEP inert mass  
30 kg/kW array  
15% Xe

Array to Jet efficiency  
50% @ 1600 s  
60% @ 2500 s  
68% @ 6000 s

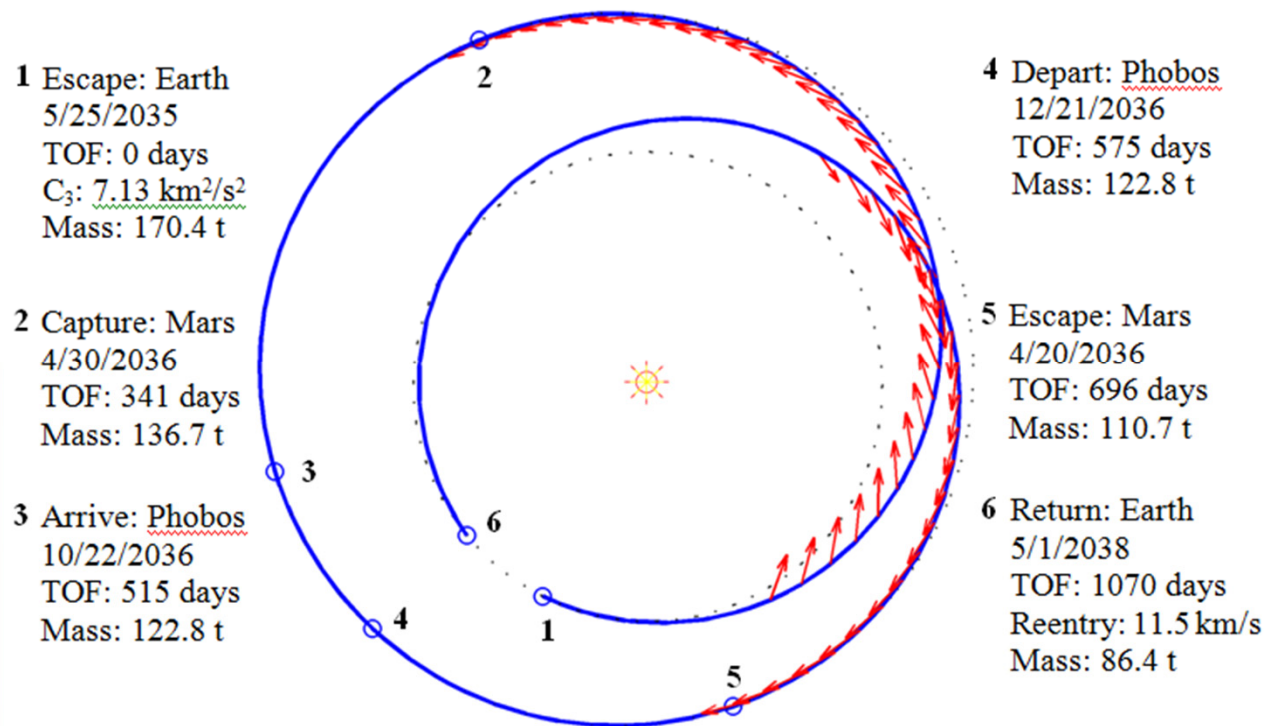


# Example NEA Mission



- 22 t transit habitat
- 10 t capsule
- 20 kg/d consumables
- 200 kW SEP
- 2000 s Isp
- Chemical departure, 450 s Isp, 25% prop.
- **165 t IMLEO**

# Example: Phobos and Deimos

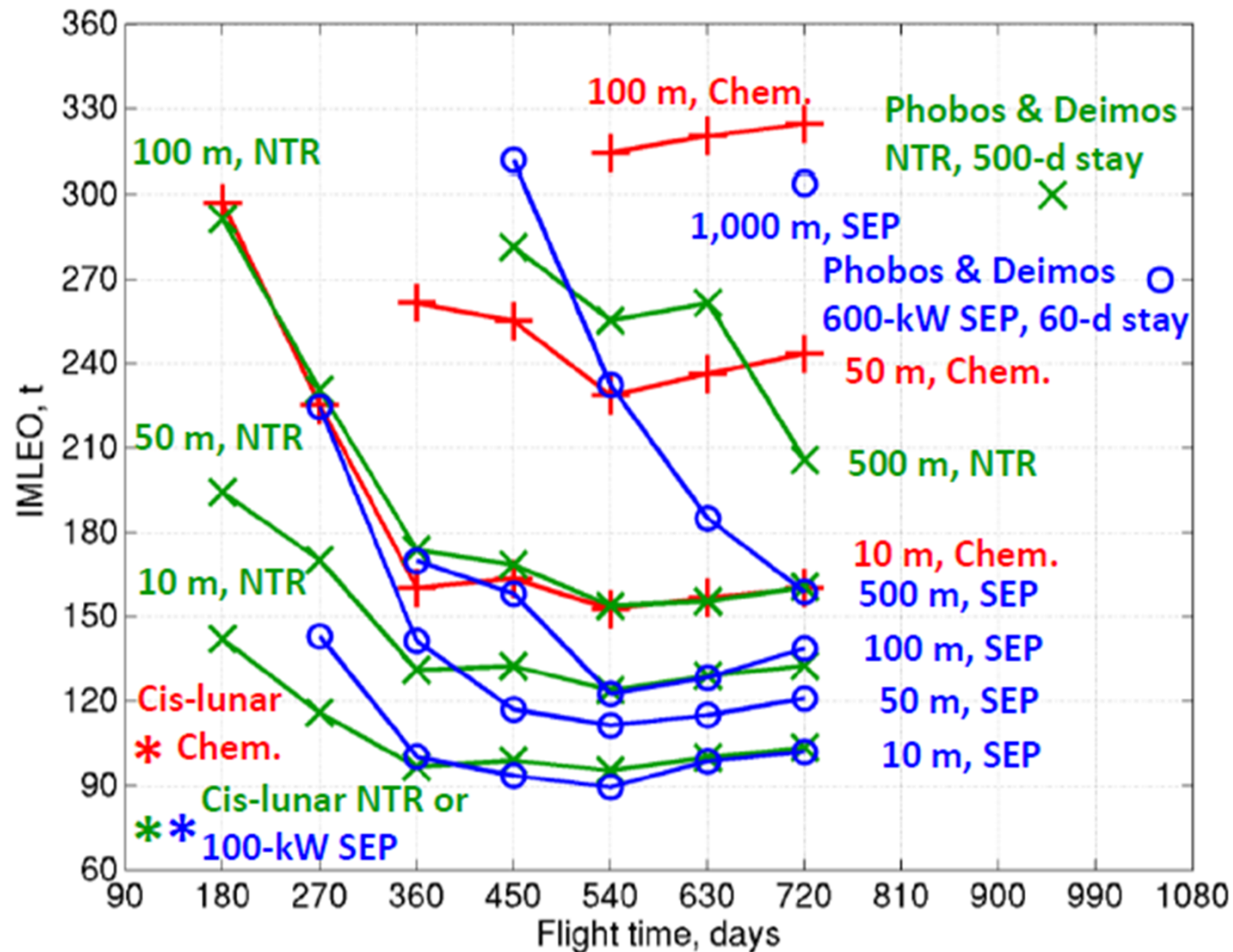


- ◆ 22 t transit habitat
- ◆ 10 t capsule
- ◆ 20 kg/d consumables
- ◆ 1600 s lsp to Mars
- ◆ 3000 s lsp LEO-HEO
- ◆ SEP inert 30 kg/kW, 15% prop.
- ◆ Chemical departure, 450 s lsp, 25% prop.

IMLEO = 270 t, SEP power = 600 kW  
Stay time = 60 days, flight time = 1080 d

NTR comparison: IMLEO = 300 t, Stay time = 500 days, flight time = 950 d  
35 % inert/propellant, 3.5 thrust/weight (core+shield), 0.2 g departure

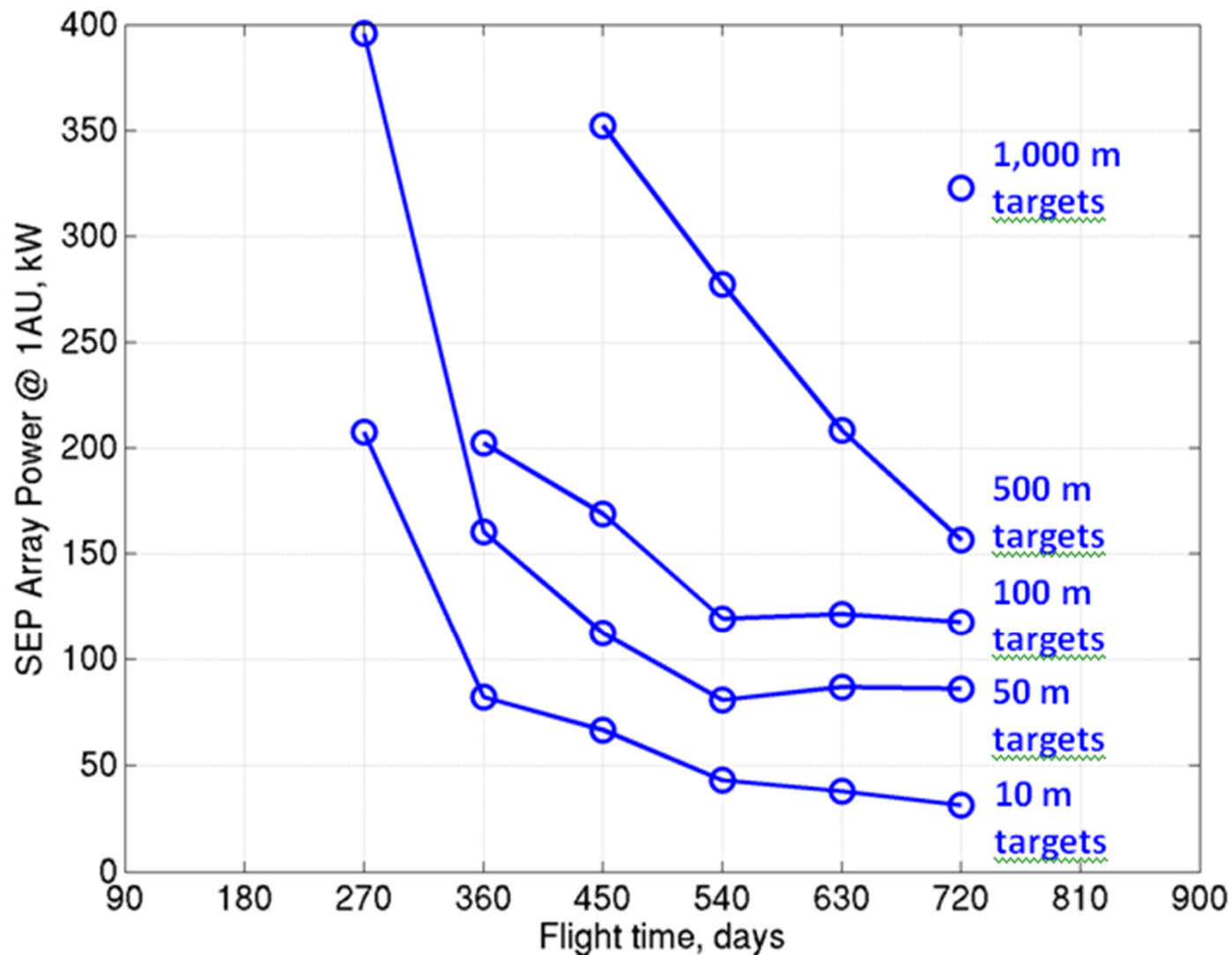
# Example Exploration Program One Mission Every 2.14 years



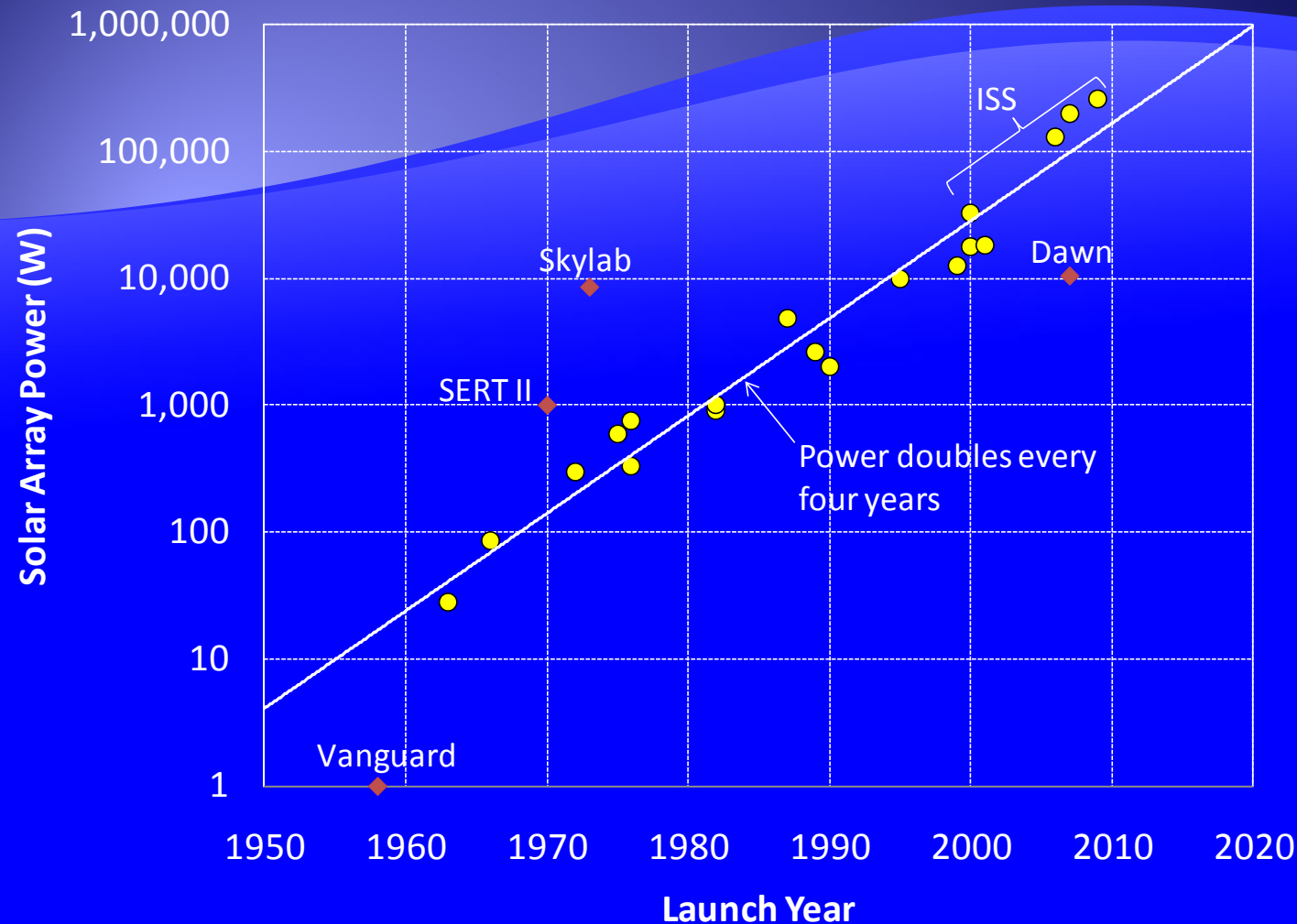
*NEA diameter  
for 15% albedo*



# SEP Power – NEO Round Trips



# Solar Array Technology Status



- Maximum solar power per spacecraft has doubled approximately every 4 years for the last 50 years.
- ISS has ~260 kW of solar array power

# EXAMPLE: Mars Cargo

100 t IMLEO launch	Time (yr) to Mars	Mass (t) delivered to atmospheric interface
200 kW, 1600 s SEP <sup>a</sup>	2.14	42.6
400 kW, 3000 s SEP	2.0	58.5
600 kW, 3000 s SEP	1.5	52.8
600 kW, 5000 s SEP	2.0	63.4
NTR <sup>b</sup>	0.8	48.8
Chemical <sup>c</sup>	0.8	30.0

<sup>a</sup>15% inert/propellant, 30 kg/kW

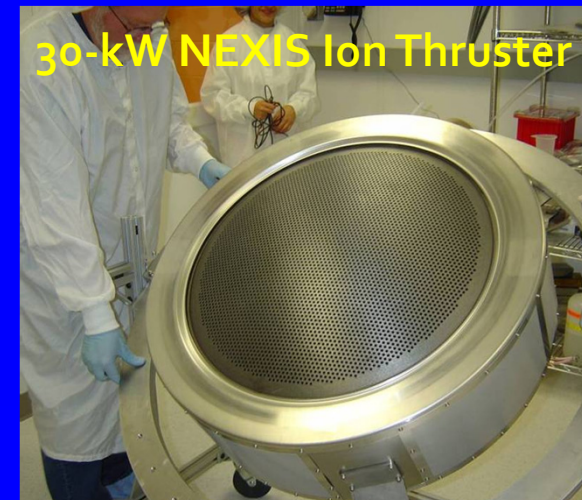
<sup>b</sup>900 s Isp, 35% inert/propellant, 0.2g thrust, 3.5 thrust/weight

<sup>c</sup>450 s Isp, 25% inert/propellant



# Electric Thruster Technology

- ◆ SEP stage would use clusters of thrusters at power levels of 50- to 100-kW each
- ◆ Ion and Hall thrusters are very scalable
  - The literature includes descriptions of ion thrusters with power levels from 10 W to 130 kW
  - Hall thrusters have been tested at power levels from 10's of W to 100 kW
- ◆ Ion thrusters most useful for spiraling cargo from LEO to HEO
- ◆ Hall thrusters provide long-life and high-thrust and are needed for deep space operations
- ◆ *A 50-kW, high-Isp, Hall thruster with an extremely long life could now be developed*
  - A 50kW laboratory model Hall thruster has been tested up to 72 kW
  - "Nested Hall" concepts could scale up to over 100 kW per thruster



# Observations

- ♦ SEP reduces launch mass for missions ranging from cis-lunar excursions, to NEO encounters, to Phobos & Deimos rendezvous
- ♦ Power levels of 100-600 kW enable SEP missions with IMLEO comparable to NTR technology with similar flight times.
- ♦ There are many paths from cis-lunar missions to Mars through the NEO capability design space
- ♦ The evolution of SEP from current levels introduces flexibility on an exploration path to Mars.